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Cooperation as a signal of time preferences

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Abstract

Many evolutionary models explain why we cooperate with non kin, but few explain why cooperative behavior and trust vary. Here, we introduce a model of cooperation as a signal of time preferences, which addresses this variability. At equilibrium in our model, (i) future-oriented individuals are more motivated to cooperate, (ii) future-oriented populations have access to a wider range of cooperative opportunities, and (iii) spontaneous and inconspicuous cooperation reveal stronger preference for the future, and therefore inspire more trust. Our theory sheds light on the variability of cooperative behavior and trust. Since affluence tends to align with time preferences, results (i) and (ii) explain why cooperation is often associated with affluence, in surveys and field studies. Time preferences also explain why we trust others based on proxies for impulsivity, and, following result (iii), why uncalculating, subtle and one-shot cooperators are deemed particularly trustworthy. Time preferences provide a powerful and parsimonious explanatory lens, through which we can better understand the variability of trust and cooperation.

Keywords: cooperation, trust, time preferences, evolution, costly signaling

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Human cooperation is inherently variable. Cooperation varies with the individual. We are not all equally likely to help an unrelated stranger in the field or in the lab, and report differing levels of cooperative behavior in surveys (Akee et al., 2018; Amir et al., 2018; Andreoni et al., 2017; Chen et al., 2013; Guinote et al., 2015; Korndörfer et al., 2015; Lettinga et al., 2020; McCullough et al., 2013; Nettle et al., 2011; Piff et al., 2010; Schmukle et al., 2019; Stamos et al., 2020; Wu et al., 2017; Wu et al., 2020; Zwirner & Raihani, 2020). Cooperation is also a function of historical and social context. Social trust tends to be lower in poorer countries, and in the aftermath of conflict or other dramatic events (Albanese & de Blasio, 2013; Balliet & Lange, 2013; Besley & Reynal-Querol, 2014; Bjørnskov, 2007; Nunn & Wantchekon, 2011; Rohner et al., 2013). For the same interaction, the norm may even be to cooperate in one society, and defect in another (Henrich, Ensminger, et al., 2010; Henrich, Heine, et al., 2010). Finally, the value of cooperation itself is variable. We place more trust in spontaneous and inconspicuous cooperators than we do in individuals who help others in deliberate or overt fashion (Bird & Power, 2015; Bird et al., 2018; Critcher et al., 2013; Everett et al., 2016; Gambetta & Przepiorka, 2014; Jordan, Hoffman, Nowak, et al., 2016; Levine et al., 2018).

Evolutionary biologists and game theoreticians explain the evolution of cooperation with non kin based on the principle of reciprocity. We trust and help those who have helped us (Axelrod & Hamilton, 1981; Trivers, 1971) or others, and have thus acquired a trustworthy reputation (Alexander, 1987; Nowak & Sigmund, 1998; Ohtsuki & Iwasa, 2006; Panchanathan & Boyd, 2003). These approaches, however, are chiefly concerned with explaining the existence of cooperation, and rarely attend to its variable nature. In most models helpful behavior varies because of exogenous noise (Boyd, 1989; McNamara et al., 2008; McNamara et al., 2004; Nowak & Sigmund, 1993). Cooperative variability remains an open question: we are unable to predict who is more prone to help, where cooperation is more likely to emerge and what determines its informational value.

The variable nature of cooperation may be studied following a framework introduced by Leimar (1997). His model is based on the assumption that individuals derive differing payoffs from cooperation, and may thus be differentially motivated to help others (see also Boyd, 1992). In line with honest signaling theory (Grafen, 1990; Zahavi, 1975), an individual's behavior in cooperative encounters will then reveal her private payoffs, and therefore her future cooperative intentions — making it reasonable to trust others based on past behavior (André, 2010; Leimar, 1997; Leimar & Hammerstein, 2001).

Leimar's model provides the general framework for our study. At first glance however, his central assumption seems unrealistic. Virtually all the resources or services that we acquire on our own may be obtained via cooperative exchanges; it is therefore difficult to conceive that some of us could systematically benefit more from cooperation than others. In order to better understand the who, the where and the what of cooperation, we must first explain why individual payoffs should vary *in general*.

One answer to these questions may lie in differences in individual time preferences. Laboratory and field experiments performed in a diversity of contexts reveal that individuals can be distinguished according to their level of preference for immediate vs. future rewards (Amir et al., 2019; Frederick et al., 2002; Kirby et al., 2002; Tanaka et al., 2010). These time preferences are stable in the

51 short to medium term (Chuang & Schechter, 2015; Meier & Sprenger, 2015),
52 and across similar decisions (Harrison et al., 2002; Ubfal, 2016).

53 Interindividual differences could originate from adaptive phenotypic plastic-
54 ity, as harsher environments make future rewards more uncertain and/or present
55 needs more pressing, and select for stronger preference for the present (Chu et
56 al., 2010; Ellis et al., 2009; Fawcett et al., 2012; Mell et al., 2021; Nettle &
57 Frankenhuys, 2020; Pepper & Nettle, 2017; Stevens & Stephens, 2010). At a
58 fundamental level, cooperation entails paying immediate costs (to help others)
59 and, following the principle of reciprocity, receiving delayed benefits (in the form
60 of future help) (André, 2010; Barclay & Barker, 2020; Leimar, 1997; Leimar &
61 Hammerstein, 2001; Nowak & Sigmund, 1998). In theory, an individual's time
62 preferences should equivalently affect *all* the payoffs she derives from coopera-
63 tive encounters.

64 In this paper, we formally explore the hypothesis that time horizon is the
65 underlying cause of the variability of human cooperation. We develop a mathe-
66 matical model of cooperation in which individuals are characterized by a hidden
67 discount rate, which remains constant throughout their life, and affects all fu-
68 ture payoffs. Individuals face strangers in a cooperative setting, and may use
69 their reputation to discriminate between trustworthy and exploitative partners.
70 Help emerges as an honest signal of time preferences in our model. Variation of
71 time horizon ensures behavioral variability at evolutionary equilibrium, which
72 stabilizes cooperation (Ferriere et al., 2002; Fishman et al., 2001; Lotem et al.,
73 1999; McNamara & Leimar, 2010; Sherratt, 2001). In addition, assuming that
74 individual time preferences vary allows us to account for all three dimensions of
75 cooperative variability.

76 First, we predict that more future-oriented individuals should be more prone
77 to help. At equilibrium in our model, trustworthy partners are individuals
78 whose time horizon surpasses a certain threshold. This result conforms with
79 empirical data. Many studies report a positive correlation between individual
80 time horizon and cooperation (Curry et al., 2008; Fehr & Leibbrandt, 2011;
81 Harris & Madden, 2002; Kocher et al., 2013; Sjøstad, 2019), although it should
82 be noted that some of the evidence is inconclusive (Barclay & Barker, 2020;
83 Wu et al., 2017). Our first result also helps explain interindividual cooperative
84 variability. In surveys and field studies, individual cooperation is associated to
85 environmental affluence (Andreoni et al., 2017; Korndörfer et al., 2015; Lettinga
86 et al., 2020; Nettle et al., 2011; Schmukle et al., 2019; Zwirner & Raihani, 2020)
87 — a variable which closely aligns with time horizon (Adams & White, 2009;
88 Amir et al., 2019; Bulley & Pepper, 2017; Griskevicius et al., 2011; Harrison
89 et al., 2002; Kirby et al., 2002; Reimers et al., 2009; Tanaka et al., 2010). Time
90 preferences have been found to mediate the relationship between environmental
91 affluence and individual investment in collective actions (Lettinga et al., 2020).

92 Second, we predict that more future-oriented populations should have access
93 to a wider range of stable cooperative opportunities. In surveys and field studies,
94 average cooperation and trust are associated to collective wealth (Albanese & de
95 Blasio, 2013; Korndörfer et al., 2015; Lettinga et al., 2020; Nunn & Wantchekon,
96 2011; Schmukle et al., 2019). Our model offers two complementary explanations
97 for these observations. Following our first result, we expect higher aggregate
98 cooperation when many individuals are future-oriented. Following our second
99 result, we expect cooperation and trust to emerge in a wider range of contexts
100 when population distribution of time preferences shifts towards the future.

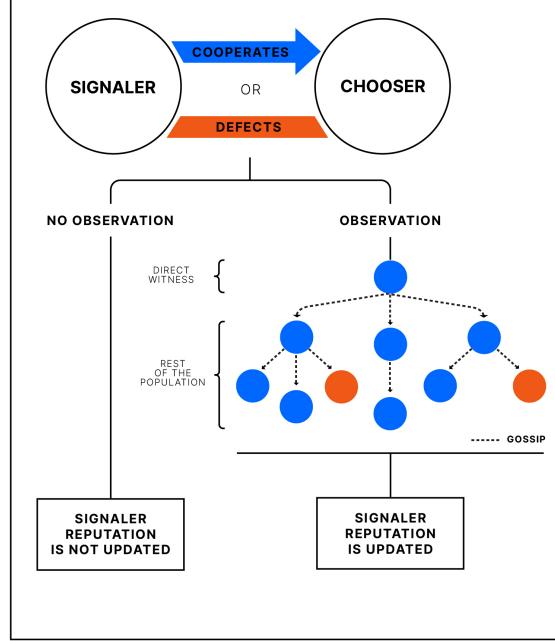


Figure 1: Reputation formation. Signaler behavior is observed with probability p and error σ by the entire population in our model ($0 < p < 1$ and $0 < \sigma < \frac{1}{2}$). This may be interpreted to reflect direct observation by one or several witnesses, and rapid social transmission of information (gossip) (Giardini & Vilone, 2016; Nowak & Sigmund, 1998, 2005). Direct observers mention their observation to several acquaintances, who in turn inform their acquaintances, etc. When this process is rapid relative to social interactions, all individuals receive information by the next trust game. Error σ can thus be seen to reflect the noisiness of social transmission: when a Signaler is observed cooperating, $1 - \sigma$ percent of individuals form a trustworthy image of that Signaler, and σ percent an exploitative image (and vice-versa with defection). We assume that new information replaces old information, and that individuals never forget. In future trust games, partners of that Signaler may condition their trust on (their private view of) her reputation.

101 Third, we predict that cooperation should be a more informative signal of
 102 time preferences when observation is unlikely, or when the cost-benefit ratio is
 103 low. Our theory may explain why we place more trust in helpful partners who
 104 maintain a low profile or make impromptu decisions (Bird & Power, 2015; Bird
 105 et al., 2018; Critcher et al., 2013; Everett et al., 2016; Gambetta & Przepiorka,
 106 2014; Jordan, Hoffman, Nowak, et al., 2016; Levine et al., 2018). Inconspic-
 107 uous cooperators are indeed less likely to be observed and, since spontaneous
 108 cooperators help more frequently (Jordan, Hoffman, Nowak, et al., 2016; Levine
 109 et al., 2018; Rand et al., 2012), they stand to gain less from the average en-
 110 counter. Both behaviors reveal strong preference for the future in our model,
 111 and therefore strong cooperative motivation.

1 Cooperating with strangers

Table 1: Payoffs for the trust game.

		Signaler	
		Cooperate (C)	Defect (D)
Chooser	Accept (A)	$(b, r - c)$	$(-h, r)$
	Reject (R)	$(0, 0)$	$(0, 0)$

We model cooperative encounters following a trust game with two roles (adapted from Jordan, Hoffman, Bloom, et al., 2016). The game consists in two stages: in the first, the "Chooser" may either accept the "Signaler" or reject partnership with that prospective partner, putting an early end to the interaction. Accepted Signalers reap reward r .

Partnership is only advantageous with trustworthy Signalers. In the second stage, the Signaler may cooperate with the Chooser, or opt to defect. Cooperation costs c and benefits the Chooser, who earns b . In contrast, defection is free and harms the Chooser, who loses h . We assume cooperation is net beneficial for Signalers: $r > c$. Payoffs are summarized in Table 1.

When in the role of Chooser, individuals always face a strange Signaler, with whom they have never interacted before, and of whom they possess no privileged information. Choosers may however condition their play on their partner's reputation. Signalers are observed with probability p , and error σ . Individuals form a trustworthy or exploitative image of Signalers based on the most recent observation (see Figure 1).

Signalers have varying time preferences. We assume that individuals engage in a large number of cooperative interactions throughout their life, and that lifetime payoffs can be calculated following a discounted utility model (Frederick et al., 2002). A Signaler's time preference is represented by her discount rate δ : obtaining payoff π at future time t is worth $(\frac{1}{1+\delta})^t \times \pi$ now. δ is positive and fixed at birth, by drawing in the population distribution of discount rates. The closer δ is to zero, the more an individual is future-oriented.

In the Supplementary Information, we give a full description of the model, and provide a thorough equilibrium analysis. Below we focus on the conditional trust and trustworthiness (CTT) strategy profile, which is defined in relation to a threshold discount rate $\hat{\delta}$, and whereby, throughout their life, (i) Choosers accept strangers given trustworthy reputation, and reject them given exploitative reputation; and (ii) Signalers cooperate when their discount rate is smaller than $\hat{\delta}$, and defect when their discount rate is larger than $\hat{\delta}$. Demonstrations for this strategy profile are detailed in the Materials and Methods section.

2 Results

2.1 Cooperative equilibrium

We show that CTT is an evolutionarily stable strategy (ESS) if and only if (Maynard Smith & Price, 1973):

$$\hat{\delta} = p \times [(1 - \sigma)(\frac{r}{c} - 1) - \sigma \frac{r}{c}] \quad (1)$$

$$\frac{\sigma h}{\sigma h + (1 - \sigma)b} < P(\delta < \hat{\delta}) < 1 - \frac{\sigma b}{\sigma b + (1 - \sigma)h} \quad (2)$$

Equation (1) specifies the strategy profile under study, by specifying the value of the threshold discount rate. Since $\hat{\delta}$ must be positive for cooperation to actually occur, we deduce an upper bound on error σ :

$$\sigma < \frac{\frac{r}{c} - 1}{2\frac{r}{c} - 1} \quad (3)$$

Cooperation is stabilized by variation of individual time preferences. Following equation (2), CTT is an ESS when at least $\frac{\sigma h}{\sigma h + (1 - \sigma)b}$ percent of individuals have a discount rate which is smaller than $\hat{\delta}$, and therefore cooperate when in the Signaler role; and at least $\frac{\sigma b}{\sigma b + (1 - \sigma)h}$ individuals are above that threshold, and therefore defect. Both fractions are positive, increasing functions of error σ : cooperation is evolutionarily stable in our model when behavior at equilibrium is sufficiently variable (Ferriere et al., 2002; Fishman et al., 2001; Lotem et al., 1999; McNamara & Leimar, 2010; Sherratt, 2001), and error sufficiently small (Giardini & Vilone, 2016).

2.2 Who: cooperators are sufficiently future-oriented individuals

At equilibrium, trustworthy Signalers are individuals whose discount rate is inferior to $\hat{\delta}$. When individuals play CTT, Signalers who cooperate pay immediate cost c and increase their chances of facing well-disposed partners in the future, once they have been observed. The value of establishing and maintaining a trustworthy reputation $\hat{\rho}$ depends on the average delay Signalers have to wait before they are observed, which is proportional to $\Delta t = \frac{1}{p}$, and on the benefit of consistently cooperating instead of defecting after observation, $\hat{\beta} = (1 - \sigma)(r - c) - \sigma r$.

We can in fact write: $\hat{\rho} = p[(1 - \sigma)(r - c) - \sigma r] = \frac{\hat{\beta}}{\Delta t}$. Since $\sum_{t=1}^{\infty} (\frac{1}{1 + \delta})^t = \frac{1}{\delta}$, an individual's social future may be represented by a single trust game whose payoffs are discounted with rate $\frac{1}{\delta}$. Signalers cooperate at equilibrium if and only if the value they attach to gaining $\hat{\rho}$ their entire future social life exceeds the immediate cost of cooperation c — mathematically, $\delta < \hat{\delta} \iff \frac{1}{\delta} \times \hat{\rho} > c$. Everything is as if trustworthy Signalers pay c to secure benefit $\hat{\beta}$ in a future trust game which occurs with probability p . (Note that $\hat{\rho}$ tends towards $r - c$ when p tends toward 1 and σ towards 0; when observation is highly faithful and certain, trustworthy Signalers pay c in order to gain $r - c$ their entire future life, with quasi-certainty.)

2.3 Where: future-oriented populations have access to a wider range of cooperative opportunities

When average discount rates are low, equation (2) is verified for a wide range of possible parameter values, including when $\hat{\delta}$ is small — i.e. when the cost-

benefit ratio $\frac{r}{c}$ of cooperation is low, and/or when observation is unlikely (small p) or unreliable (large σ). Even the most demanding forms of cooperation are stable in sufficiently future-oriented populations.

2.4 What: cooperation reveals underlying time preferences

Cooperation evolves as a signal of time preferences. At equilibrium, when a Signaler cooperates, she reveals that her discount rate is under $\hat{\delta}$. What's more, cooperation emerges as a signal, and not merely a cue, of Signaler time preferences (Biernaskie et al., 2018). Cooperation is selected because it affects Choosers' behavior: future-oriented Signalers cooperate in order to increase their chances of being trusted in the future; effectively paying c now in order to gain $\rho > 0$ their entire future life. In contrast, cooperation cannot evolve in the absence of such an effect. If for instance Choosers accept whatever the information they are presented with, cooperative Signalers do not increase their relative chances of being trusted in the future; in such a case, they would pay c now to gain nothing later.

In addition, the informative value of cooperation increases when $\hat{\delta}$ decreases. When a Signaler helps given small cost-benefit ratio $\frac{r}{c}$ or unlikely observation p , she reveals that her temporal discount rate must be small — and that she could therefore potentially be trusted in a wide array of cooperative interactions.

3 Discussion

In this paper, we have shown that cooperation can be understood as a signal of time preferences, using a formal model. We derived three predictions from our model: (i) future-oriented individuals should be more motivated to cooperate, (ii) future-oriented populations should have access to a wider range of cooperative opportunities, and (iii) cooperators who reveal stronger preference for the future should inspire more trust. These results shed light on the variability of cooperative behavior and trust.

3.1 Environment and cooperation

Results (i) and (ii) help explain why individual and aggregate cooperation are associated to environmental affluence in large representative surveys (Albanese & de Blasio, 2013; Korndörfer et al., 2015; Lettinga et al., 2020; Nunn & Wantchekon, 2011; Schmukle et al., 2019), in field studies (Andreoni et al., 2017; Nettle et al., 2011; Zwirner & Raihani, 2020) and a natural experiment (Akee et al., 2018) — since people in more privileged circumstances tend to display stronger preferences for the future (Adams & White, 2009; Amir et al., 2019; Bulley & Pepper, 2017; Griskevicius et al., 2011; Harrison et al., 2002; Kirby et al., 2002; Reimers et al., 2009; Tanaka et al., 2010) (see also de Courson & Nettle, 2021).

Due to adaptive phenotypic plasticity, the environment in which we grow up and live may in fact directly fashion our time preferences; and therefore fashion our cooperative inclinations (Ellis et al., 2009; Nettle & Frankenhuys, 2020; Pepper & Nettle, 2017). Evolutionary models show that it is adaptive to be more

present-oriented in adverse circumstances, i.e. when future rewards are uncertain (Fawcett et al., 2012; Stevens & Stephens, 2010), or when present needs are pressing (Chu et al., 2010; Mell et al., 2021). Interindividual differences in time preferences and cooperation could thus arise from an adaptive plastic response to one’s environment, for either of these reasons. In support of this hypothesis, a recent study finds that present biases partially mediate the relationship between affluence and investment in collective actions (Lettinga et al., 2020), while a meta-analytic review finds a negative correlation between early-life stress and self-reported cooperation (Wu et al., 2020).

It should be noted that the evidence from behavioral experiments is mixed. While some economic games have produced a positive association between affluence and cooperation (Balliet & Lange, 2013; Henrich, Ensminger, et al., 2010; Korndörfer et al., 2015; McCullough et al., 2013; Nettle et al., 2011; Schmukle et al., 2019), other laboratory experiments yield the opposite association (Amir et al., 2018; Chen et al., 2013; Guinote et al., 2015; Piff et al., 2010), or no effect at all (Stamos et al., 2020; Wu et al., 2017). The previously mentioned meta-analysis finds no significant overall correlation (Wu et al., 2020). In some instances, this discrepancy is attributable to small sample sizes (Korndörfer et al., 2015; Stamos et al., 2020). More largely, the generalizability and ecological validity of many laboratory experiments can be questioned; in particular when only one economic game is performed. Recent studies find that measures derived from a single economic game do not correlate with self-reported cooperation or real-life behavior, but that a general factor based on several games does (Galizzi & Navarro-Martinez, 2019; McAuliffe et al., 2019).

3.2 Trust depends on revealed time preferences

Result (iii) helps explain why we infer trustworthiness from traits which appear unrelated to cooperation, but happen to predict time preferences. We trust known partners and strangers based on how impulsive we perceive them to be (Peetz & Kammrath, 2013; Righetti & Finkenauer, 2011); impulsivity being associated to both time preferences and cooperativeness in laboratory experiments (Aguilar-Pardo et al., 2013; Burks et al., 2009; Cohen et al., 2014; Martinsson et al., 2014; Myrseth et al., 2015; Restubog et al., 2010). Other studies show we infer cooperative motivation from a wide variety of proxies for partner self-control, including indicators of their indulgence in harmless sensual pleasures (for a review see Fitouchi et al., 2021), as well as proxies for environmental affluence (Moon et al., 2018; Williams et al., 2016).

Time preferences further offer a parsimonious explanation for why different forms of cooperation inspire more trust than others. When probability of observation p or cost-benefit ratio $\frac{r}{c}$ are small in our model, helpful behavior reveals large time horizon — and cooperators may be perceived as relatively genuine or disinterested. We derive two different types of conclusion from this principle.

3.3 Inconspicuous cooperation

First, time preferences explain why we trust our partners more when they cooperate in an inconspicuous manner (see also Bird & Power, 2015; Bird et al., 2018; Hoffman et al., 2018; Quillien, 2020). In our model, the average delay cooperators have to wait before help can be profitable varies like $\Delta t = \frac{1}{p}$. Given

smaller probability of observation p , helpful individuals literally reveal they are able to wait for a longer amount of time. In contrast, when immediate rewards are added (e.g. when blood donors are promised payment), help becomes much less informative; and less valuable to the more genuinely prosocial (Benabou & Tirole, 2003).

In particular, only acutely future-oriented individuals will help when observability p is tiny. Their cooperation is akin to a "message in a bottle": a powerful demonstration of their intrinsic cooperativeness, which, so long as $p \neq 0$, will eventually be received by others. This could explain why some of us cooperate in economic games which are designed to make our help anonymous (Raihani & Bshary, 2015), so long as we assume that anonymity is never absolutely certain (see also Delton et al., 2011).

3.4 Spontaneous cooperation

Second, time preferences explain why we trust our partners more when they cooperate spontaneously — when their behavior appears more natural, unhesitant, intuitive, uncalculating or underlain by emotion (Critcher et al., 2013; Everett et al., 2016; Gambetta & Przepiorka, 2014; Jordan, Hoffman, Nowak, et al., 2016; Levine et al., 2018). Since they help their partners more frequently (Jordan, Hoffman, Nowak, et al., 2016; Levine et al., 2018; Rand et al., 2012), including when defection is tempting, more spontaneous cooperators enjoy lower expected payoffs in the typical encounter (see also Hoffman et al., 2015). Greater spontaneity could thus indicate willingness to help given smaller values of $\frac{r}{c}$; and therefore stronger preference for the future.

3.5 Time preferences and other partner qualities

Our analysis has fixated on time preferences. This is somewhat arbitrary. Many other characteristics affect our cooperative interests, and are revealed by our social behavior — underlying costs and benefits (Jordan, Hoffman, Bloom, et al., 2016; Jordan, Hoffman, Nowak, et al., 2016), revelation probability (Hoffman et al., 2018), and, when interacting with known associates, specific commitment to the shared relationship (Barclay, 2020; Barclay & Barker, 2020; Barclay et al., 2021; Bird et al., 2018; Quillien, 2020) (this latter dimension is absent in our model). These qualities shape our strategic interests in a given social context: we stand to gain more from cooperation when it involves a partner we know and are committed to; and when it occurs in a social network we value and are embedded in, where we should enjoy higher observability and payoffs. Yet, context changes fast. We can help a close friend today, and donate anonymously tomorrow.

In contrast to other partner qualities, time preferences appear remarkably stable. Communication of time preferences is likely to be a fundamental element of human cooperation. It may even underlie other facets of our social life. The larger our time horizon, the more likely we are to invest in our social surroundings, via dyadic help as well as collective actions or policing. Contribution to public goods (Gintis et al., 2001) and prosocial punishment (Jordan, Hoffman, Bloom, et al., 2016), which function as signals of cooperative intent, may also rely on communication of time preferences.

Materials and methods

This section gives a sketch of the evidence regarding the conditional trust and trustworthiness strategy profile, in a simplified setting. For a full description of the model, and a thorough equilibrium analysis, see the Supplementary Information.

Two types of players engage in a repeated trust game: Choosers and Signalers. In each round, a Chooser faces a Signaler she has never encountered before. She may first accept or reject the Signaler, putting an early end to the interaction. If accepted, the Signaler reaps reward r , and may then cooperate or defect. Cooperation involves the Signaler paying cost c for the Chooser to gain b ; defection is free, and harms the Chooser, who loses h .

Choosers may condition their strategy on their private view of the Signaler's reputation. Each time a Signaler acts, she is observed with probability p . When a Signaler is observed cooperating, $1 - \sigma$ percent of Choosers receive information \mathcal{T} , correctly indicating that the Signaler behaved in a trustworthy manner; and the remaining σ percent receive information \mathcal{E} , falsely indicating exploitative behavior (and vice-versa with defection). We assume new information replaces old information.

Signalers may condition their strategy on their discount rate δ . To simplify things, we assume here that Signalers play a stationary strategy (always cooperate, or always defect), and that they are initially certain to be accepted (before the first observation). We relax both these assumptions in the Supplementary Information, and obtain the same results. δ is fixed at birth, by drawing in a continuous probability distribution which characterizes the Signaler population. Signalers engage in a large number of rounds of the repeated trust game, a payoff t rounds in the future being discounted by factor $(\frac{1}{1+\delta})^t$ now.

According to the conditional trust and trustworthiness (CTT) strategy profile, (i) Choosers accept given trustworthy reputation \mathcal{T} , and reject given exploitative reputation \mathcal{E} ; and (ii) Signalers cooperate if their discount rate is smaller than a certain threshold value $\hat{\delta}$, and defect if their discount rate is larger than $\hat{\delta}$. We show that CTT is an evolutionarily stable strategy (ESS) (Maynard Smith & Price, 1973) under the conditions set by equations (1-2), by computing equilibrium and deviation payoffs for Signalers first, and Choosers second.

Signaler equilibrium payoffs

We consider a Signaler of discount rate δ . Let Π_C and Π_D be the lifetime discounted payoff she can expect from cooperation and defection respectively. We show that when the value of $\hat{\delta}$ is given by equation (1), the Signaler stands to strictly lose from deviation from CTT.

Let us first calculate Π_C . When the Signaler cooperates, she gains $r - c$ every round she is accepted. She will eventually be observed, from which point she can expect to be accepted $1 - \sigma$ percent of the time in equilibrium, in rounds where she is paired with a Chooser who has (correctly) received information \mathcal{T} . In other words, she eventually gains payoff $\Pi_C^\infty = \sum_{t=0}^{\infty} (\frac{1}{1+\delta})^t (1 - \sigma)(r - c) = \frac{1+\delta}{\delta} (1 - \sigma)(r - c)$, starting from the point of first observation.

In the initial round however, she is certain to be accepted, and gain $r - c$. Observation affects her payoffs starting in the next round, which are discounted by factor $\frac{1}{1+\delta}$: if she is observed, she gains Π_C^∞ starting the next round, if not, she continues to gain payoff Π_C . In other words, we have:

$$\Pi_C = r - c + \frac{p \times \Pi_C^\infty + (1 - p) \times \Pi_C}{1 + \delta}$$

From which we deduce:

$$\Pi_C = (r - c + \frac{p \times \Pi_C^\infty}{1 + \delta}) \times \frac{1 + \delta}{p + \delta}$$

365 We can apply an analogous reasoning to calculate Π_D . When the Signaler defects,
 366 she gains r every round she is accepted. After the first observation, the Signaler can
 367 expect to be accepted σ percent of the time, when paired with a Chooser who has
 368 (incorrectly) received information \mathcal{T} . She eventually gains: $\Pi_D^\infty = \sum_{t=0}^{\infty} (\frac{1}{1+\delta})^t \sigma r =$
 369 $\frac{1+\delta}{\delta} \sigma r$. Starting from the initial round, she therefore gains:

$$\Pi_D = r + \frac{p \times \Pi_D^\infty + (1 - p) \times \Pi_D}{1 + \delta}$$

370 Which yields:

$$\Pi_D = (r + \frac{p \times \Pi_D^\infty}{1 + \delta}) \times \frac{1 + \delta}{p + \delta}$$

371 By comparing both expressions, we deduce that the Signaler strictly benefits from
 372 cooperation if and only if the cost of cooperating now is smaller than the benefit of
 373 receiving Π_C^∞ instead of receiving Π_D^∞ in the future, with probability p :

$$\Pi_D < \Pi_C \iff c < p \times \frac{\Pi_C^\infty - \Pi_D^\infty}{1 + \delta}$$

374 And, by replacing Π_C^∞ and Π_D^∞ by their values, we deduce the logical equivalence:

$$\Pi_D < \Pi_C \iff \delta < p \times [(1 - \sigma)(\frac{r}{c} - 1) - \sigma \frac{r}{c}]$$

375 Under condition (1), the Signaler therefore always stands to strictly lose from
 376 deviation from CTT. If her discount rate δ is smaller than $\hat{\delta}$, she strictly gains on
 377 average from cooperating her whole life instead of defecting her whole life; if conversely,
 378 $\delta > \hat{\delta}$, she strictly benefits from defecting. Note that CTT does not prescribe behavior
 379 for the Signaler when her discount rate is precisely equal to the threshold. Here, we
 380 neglect this possibility, based on the fact that the population distribution of discount
 381 rates is continuous (we come back to this in the Supplementary Information).

382 Chooser equilibrium payoffs

383 We show that in equilibrium, Choosers stand to strictly lose from deviation from CTT
 384 when equation (2) is verified. Let us first consider a Chooser faced with information
 385 \mathcal{T} . If the Chooser rejects the Signaler, she gains nothing; if she accepts, she stands to
 386 gain expected benefit $P(C|\mathcal{T}) \times b + P(D|\mathcal{T}) \times (-h) = P(C|\mathcal{T})(b + h) - h$. Accepting
 387 given \mathcal{T} is therefore strictly beneficial iff:

$$P(C|\mathcal{T}) > \frac{h}{b + h}$$

388 Let $\tau = P(C) = P(\delta < \hat{\delta})$ be the equilibrium probability that the Signaler is
 389 trustworthy. Following Bayes' rule, $P(C|\mathcal{T}) = \frac{P(\mathcal{T}|C)}{P(\mathcal{T})} \times \tau$. The above inequality can
 390 be rewritten as:

$$\frac{1 - \sigma}{\tau(1 - \sigma) + (1 - \tau)\sigma} \times \tau > \frac{h}{b + h}$$

391 This is equivalent to:

$$\tau > \frac{\sigma h}{\sigma h + (1 - \sigma)b} \quad (2a)$$

Let us now consider a Chooser faced with information \mathcal{E} . An analogous calculation shows that rejecting given \mathcal{E} is strictly beneficial iff:

$$P(C|\mathcal{E}) < \frac{h}{b+h}$$

Using Bayes' rule, we find: $P(C|\mathcal{E}) = \frac{P(\mathcal{E}|C)}{P(\mathcal{E})} \times \tau = \frac{\sigma}{\tau\sigma + (1-\tau)(1-\sigma)} \times \tau$. By replacing in the above inequality, we deduce that rejection given \mathcal{E} is strictly beneficial iff:

$$\tau < 1 - \frac{\sigma b}{\sigma b + (1-\sigma)h} \quad (2b)$$

Combining equations (2a) and (2b), and replacing $\tau = P(\delta < \hat{\delta})$ we deduce equation (2). Under that condition, Choosers therefore stand to strictly lose from deviation from CTT. We deduce that CTT is an ESS under the conditions set by equations (1-2): any mutant is strictly counter-selected. We show in the Supplementary Information that we in fact have an equivalence; CTT is an ESS if and only if both equations are verified.

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